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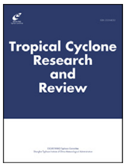

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Forecasting tropical cyclone rainfall and flooding hazards and impacts

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Abstract

This review summarizes the rapporteur report on advances in monitoring and forecasting of rainfall associated with tropical cyclones (TCs) and its impact during 2014–18, as presented to the 10th International Workshop on TCs (IWTC-10) held in Bali, Indonesia during 5th – 9th December 2022. Major physical processes that can modulate TC rainfall distribution, including topography, storm motion, vertical wind shear, and intensity, along with the fundamental physics of rain bands and clouds as simulated by numerical models, diurnal variation of rainfall, and various synoptic and mesoscale features controlling the rainfall distribution are briefly discussed. Improvements to the dynamic core and physical processes in global models are providing useable forecasts nearly up to 7 days. This report also summarizes, some tools that have been developed to predict TC rainfall. Lately there is a tendency for operational forecasting centers to utilize multi-model ensemble systems for rainfall forecasting that demonstrate superior performance than individual models, ensemble members, or even single model ensembles. Major impacts include pluvial and fluvial floods, and landslides. The techniques developed by various forecasting centers to assist in predicting and communicating the impacts associated with these events are also presented in this report.

Keywords: Rainfall; Flooding; Storm size; Topography

1. Introduction

In this study, the latest research on tropical cyclone (TC) rainfall and flooding, forecast and warning practices from different forecasting centers, challenges in forecasting and future plan have been discussed.

TC rainfall and associated flooding poses a significant hazard that can extend hundreds of kilometers inland from the coast. Flooding from heavy rainfall leads to fatalities more often in TCs than any other hazard (Rappaport, 2014), and TCs account for a significant percentage of the total number of flood-related fatalities in countries most often directly impacted by landfalling events (Hu et al., 2018). Therefore, improving the accuracy and communication of rainfall and flooding forecasts is of critical importance to mitigate the impacts of TCs. Some of the costliest and deadliest TCs in recent years have delivered massive tolls largely because of rainfall induced flooding.

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TCs can account for substantial percentages of both average annual rainfall and total extreme rain events in different regions of the globe. Khouakhi et al. (2017) found that TCs contributed well over 30 percent of the annual rainfall in some arid regions, such as northwest Australia or Baja California, and in some regions with frequent cyclone activity, such as southeast China and the northern Philippines. Additionally, TCs account for a significant percentage of extreme rainfall events. Globally, between 13 and 31 percent of daily rainfall events exceeding ~100 mm are caused by TCs, depending on the basin (Prat and Nelson 2016). In some regions, TCs can account for the majority of extreme rainfall events, depending on how exactly the term is defined (Barlow 2011; Khouakhi et al., 2017).

Forecasts of TC rainfall are generally influenced by eight main factors.

- **Movement:** Slow forward motion can produce more rainfall. And the storm track determines the location of the rain.
- **Storm size:** The larger the storm, the greater the area typically receiving rain. Additionally, for the same forward motion, a larger storm will tend to produce more rainfall.
- **Topography:** Enhances rainfall in upslope areas, but decreases rainfall past the spine of the mountains. The upslope area in a tropical cyclone will depend on the storm location.
- **Moisture:** Entrainment of dry air can redistribute and/or reduce the amount of precipitation; increased moisture can increase rainfall.
- **Instability:** Greater instability will tend to support higher rainfall rates.
- **Diurnal cycle:** The heaviest rainfall will generally occur near the storm center overnight, with outer band rainfall favoured during the daytime.
- **Vertical wind shear:** The heaviest rainfall will tend to be concentrated downshear of the storm center.
- **Other interactions:** Interactions with troughs, fronts, and jets, and extratropical transition can greatly modify rainfall distribution.

Conceptual models and heuristics based on these factors can be used in conjunction with improving numerical weather prediction (NWP) model guidance to produce more accurate forecasts, and better communicate expectations to officials and the public. For example, slower and larger cyclones will tend to increase the likelihood of heavy rainfall, over a specific area for an extended period. This has significant implications in a changing climate, as Kossin (2018) found that the forward speed of TCs has decreased by 10 percent since 1949. Compounding matters is that the average TC rainfall rate has increased by about 1 percent per year over the past couple of decades (Guzman and Jiang, 2021). In many TCs, flood impacts are caused by compound events with multiple factors, such as precipitation and storm surges leading to flooding in coastal areas. An ultimate goal would be to predict the flood inundation in a fully integrated and probabilistic system based on precipitation, river modelling and storm surge.

2. Tropical cyclone rainfall patterns and intensity

Rainfall associated with TCs does not necessarily adhere to simple rules or correlate directly with storm intensity, measured by maximum sustained wind or minimum central pressure. Nevertheless, research does indicate some important findings that can be applied to understanding and predicting TC rainfall location, extent, and intensity.

TCs that are considered “weak” by traditional intensity measures can still produce extremely heavy rainfall during and after landfall. Such extreme events are very challenging to operational forecasts and often lead to disasters in the affected regions. Tropical Storm Rumbia in 2018 made its landfall in Shanghai with weak intensity but led to long-lasting and significant rainfall in East China. Tang et al. (2021) found that the low-level convective instability and the deep-layer environmental vertical wind shear played an important role in deepening the inflow boundary layer and the redevelopment of the secondary circulation, thus contributing to the heavy rainfall in the northeast quadrant of Rumbia after its landfall. Similar extreme events have occurred elsewhere in the world from TCs of “weak” intensity, such as Tropical Storm Imelda in 2019, which produced a maximum rainfall total of 1125 mm (44.29 inches) in southeast Texas over the course of a few days. Slow forward motion of a TC is often a contributing factor.

Nevertheless, there is some observed relationship between daily rainfall accumulation and a tropical cyclone's daily maximum surface wind speeds (Cerveny and Newman, 2000). In China, both observational studies (Jiang et al., 2018; Qiu et al., 2018) and simulation studies (Xia et al., 2019) show that the slow (fast) translation speed, strong (weak) intensity of typhoons and the strengthening (weakening) intensity of the monsoon are conducive to the enhancement (weakening) of extreme precipitation in key areas in China.

Satellite-based rainfall estimates can provide a valuable source of information when evaluating TC rainfall patterns. The Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM) (IMERG) Final Run product from the GPM mission during 2001–2020 has been used in Yu et al. (2022) to investigate the relationship between the TC radius of maximum wind (RMW) and the rainfall characteristics and evolution during TC landfall over China. Results reveal that small TCs have higher rain rates with higher axi-symmetry than large TCs. Though both small and large TCs have rainfall within a radius of 5° latitudes, the rainfall occurs within a distance of up to 10 times of the RMW in small TCs compared to within 5 times of the RMW in large TCs. Results also show that higher TC intensity may partly contribute to higher rain rate during landfall in smaller TCs than in larger TCs. The finding of most rainfall occurring within 5° latitude mimics findings from Matyas (2010) that found the radius of tropical storm force winds and that the radius of the outermost closed isobar (ROCI) encompass a large portion of the TC rainfall pattern.

TC rainfall patterns can also be heavily influenced by vertical wind shear, and the effect can happen nearly instantaneously as detailed in Wingo and Cecil (2010). Rainfall is displaced down shear and to the left (right for Southern Hemisphere) of the shear vector, and the magnitude of the displacement increases with stronger shear. Wind shear can also help identify where heavy rain is less likely, with heavy rain rates relatively rare in the upshear-right quadrant of a TC. Interactions with troughs and jet streaks can modify the rainfall pattern as well, and even produce heavy rainfall about 1000 km poleward of recurving TCs via a predecessor rain event (PRE) as outlined in Galarneau et al. (2010). Studies by Bao et al. (2019, 2020), Dai et al. (2021), Dunion et al. (2014), Huang et al. (2022) further highlight the role of various factors affecting the TC rainfall.

3. Tropical cyclone rainfall observations

Rainfall observations are crucial to real-time assessment of tropical cyclone rainfall, issuance of warnings and updated forecasts at shorter lead times, and historical documentation, which can also be used to refine forecast techniques. Observations are typically either land-based rain gauges that can directly report rainfall or remote sensing techniques involving radar or satellite that can provide estimates with more continuous spatial coverage. There is considerable variability across the world in the density and availability of observations, although basically all Regional Specialized Meteorological Centers (RSMCs) and nations surveyed reported using a combination of these observation sources.

The most reliable source of observations continues to be rain gauges, with a combination of automated stations and manually retrieved measurements. To have a good spatial representation of rainfall just from gauge reports would require a dense network of measurements. For instance, Meteo-France operates nearly 100 rain gauges on the small, but mountainous, island of La Reunion (~50 km diameter with a 3000 m peak). That offers considerable coverage, but still sometimes does not capture relevant detail. Strategically placed gauges in areas of significant interest, such as vulnerable stream basins or urban areas, can provide valuable information even in isolation, and can sometimes allow meteorologists to infer rainfall information in surrounding areas. Some nations also document impacts from flooding and landslides, both from manual reports and automated stream gauges, in coordination with their hydrological departments. Volunteer observation networks, such as Community Collaborative Rain, Hail and Snow (CoCoRaHS) and the Cooperative Observer Network (CoN) in the United States (Goble et al., 2019), can enable reliable rainfall reports at a greater density and in between automated observations (the two networks average over 14,000 reports per day), making it more likely to sample localized, extreme rainfall events.

More reliable methods of filling gaps between rain gauges include radar and satellite estimates. Radar coverage is far from universal around the world, and can be unevenly distributed even within individual countries. However, when available, radars can provide reliable estimates of rainfall. Satellite rainfall estimates will provide greater spatial coverage in areas with more limited rain gauge and radar coverage, and therefore are widely used and applied. Satellite products such as IMERG, which integrate multiple data sources including microwave data, are preferred by some meteorological departments. Additionally, satellite imager channels are regularly used to monitor the development of more intense convection and rain bands.

Although rainfall information can always be viewed as an individual dataset, several nations produce a multi-sensor analysis of rainfall at regular intervals during tropical cyclones, and this incorporates the strengths of each observational dataset. For example, India produces charts based on satellite, Doppler radar, and ground observations every 3 h, and on an hourly basis when TCs approach the coasts, as a standard operating procedure (IMD, 2021). India Meteorological Department (IMD) and National Center for Medium Range Weather Forecasting (NCMRWF) Center prepare satellite and rain gauge merged plots. Typical IMD-NCMRWF satellite rain gauge merged plots during life period of TC Burevi are presented in Fig. 1.

As another example, the United States leverages the Multi-Radar Multi-Sensor (MRMS) system, which integrates data from about 180 radars, other atmospheric and satellite data, and rain gauge observations to create a seamless mosaic at high spatial and temporal resolution (Zhang et al. 2016). MRMS data is integrated directly into Flooded Locations and Simulated Hydrographs (FLASH) products, which compare MRMS rainfall to static and dynamic thresholds, such as average annual recurrence intervals, and produce forecasts from distributed hydrologic models, to provide important warning decision aids at the flash flood scale (Gourley et al. 2017). FLASH shows considerable promise in helping identify situations with more significant flash flood impacts (Gerard et al., 2021) (Fig. 2).

A few other important notes on rainfall observations include the increasing use of artificial intelligence to improve observational data quality, as with Meteo-France and the Cosparin project. Additionally, accurate measurements of precipitation microphysics play a critical role in the improvement of rainfall forecasts along with their parameterization in numerical models. And finally, preserving historical rainfall data is important, given its increasing use in verifying forecasts, and refining some statistical and analog forecast techniques. One such project is the Tropical Cyclone Rainfall Database at the U.S.-based Weather Prediction Center (WPC).

4. Methods for TC rainfall forecast

This section summarizes the methods used by different centers for forecasting the rainfall associated with TCs.

4.1. Analog and statistical forecast methods for TC rainfall

Numerous RSMCs and nations reported using or evaluating analog and statistical approaches to rainfall forecasting. These techniques may use some basic forecast data, either from an official forecast from a meteorological center, or a numerical model, but overall seek to compare a current storm to past storms of similar characteristics.

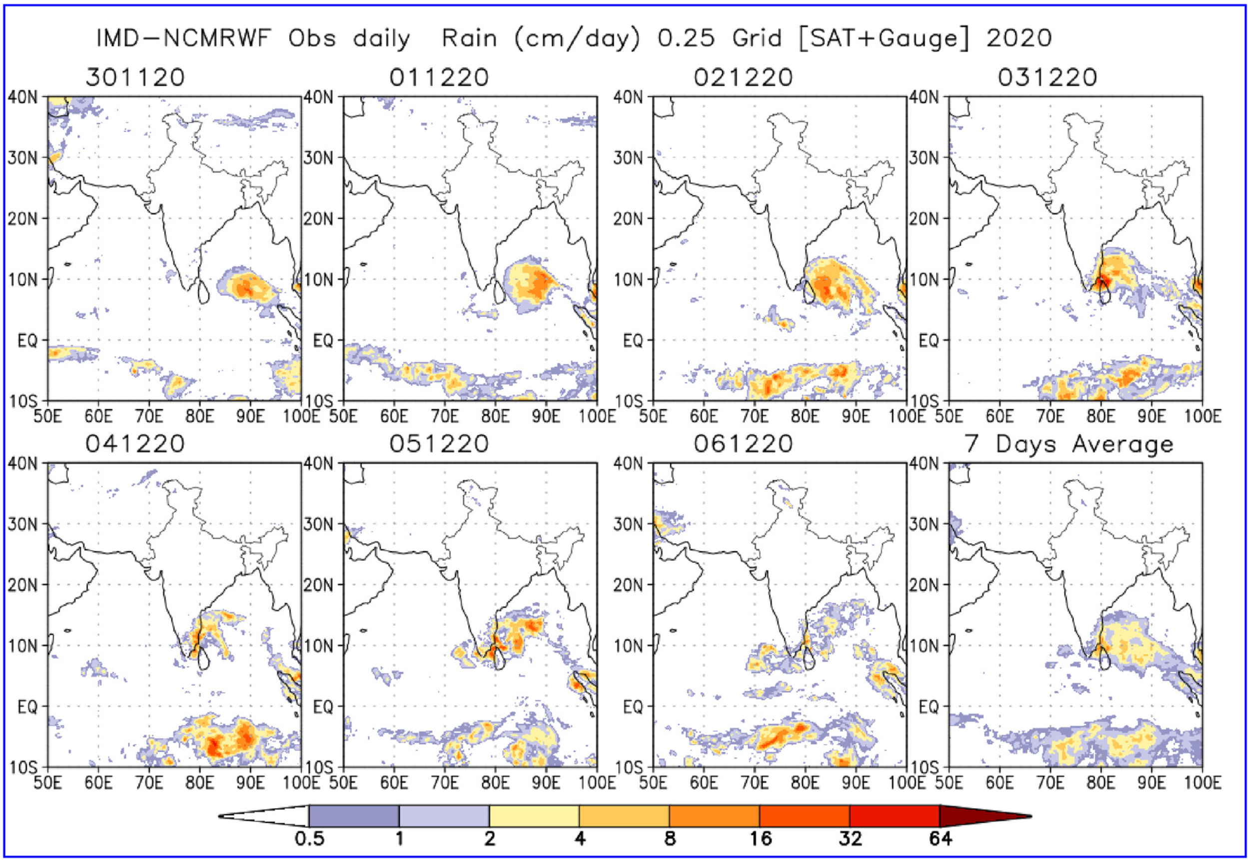


Fig. 1. Merged satellite & rain gauge data during Cyclonic storm ‘Burevi’ which affected both Sri Lanka and India in December 2020 (New Delhi, 2021).

The Dynamical Statistical Analog Ensemble Forecast (DSAEF), developed in China, is one such example, and it includes four steps: (i) forecast typhoon track, (ii) construct generalized initial value (GIV), (iii) identify analogs from historical observations, and (iv) produce an ensemble forecast of typhoon precipitation (Chenchen et al., 2020; Ding et al., 2020; Ren et al., 2020; Jia et al., 2022) (Fig. 3). The most recent version (Fig. 3) has shown significant improvements, and is superior to ECMWF, GRAPES, GFS and SMS-WARMS (Shanghai regional model) in forecasting accumulated rainfall of ≥250 mm and ≥100 mm. Several of the cited studies noted forecast improvements after including TC intensity data, and combining the dynamical forecast with initial condition analogs from historical observations.

Kim et al. (2020) established a new statistical prediction model based on the principle of track similarity where historical TC track and data were observed to optimize the typhoon-induced accumulated rainfall (TAR) over China. The new approach used Fuzzy C- Means (FCM) clustering to select typhoons with the most similar tracks, and then correct and average their rainfall (Fig. 4).

In the Philippines, Bagtasa established an analog forecast technique from a historical dataset in 2021. Tropical cyclones with similar tracks were used to create a composite rainfall map to aid in prediction of rainfall (Fig. 5). The analog technique performed better than the WRF model for intense and inland rainfall prediction, but it did underestimate extreme rain values.

Likewise, the Weather Prediction Center (WPC) in the United States uses a program called CLIQR to search for climatologically analogs in the U.S. using the forecast position, motion, size and strength of the cyclone based on the top analogs. WPC can then search an internal archive of tropical cyclone rainfall in the U.S. dating back to 1956, which are scored based on similarity. Forecasters can then evaluate the applicability to the current situation.

While many of these techniques are applied at the scale of a nation or tropical cyclone basin, smaller scale analog and statistical techniques can still provide valuable information. For example, Li et al. (2020) utilized a nonparametric statistical scheme to forecast TC rainfall in Guangdong province, China to better predict the range of rainfall that occurred.

Additionally, machine learning and artificial intelligence systems show promise in further enhancing these analog and statistical methods of rainfall predication. Liu et al. (2021) introduced a machine learning system with an analog identification method for tropical cyclone rainfall, and Wang et al. (2022) presented a review paper on current forecasting of tropical cyclones using machine learning methods.

Lu et al. (2022) has established an optimized and physics-based model for the simulation of tropical cyclone precipitation, named parameterized Tropical Cyclone Precipitation Model (TCPM). This model described the risk of TC rainfall hazards in China and considers the effect of complex terrain from three perspectives, including slope, roughness and

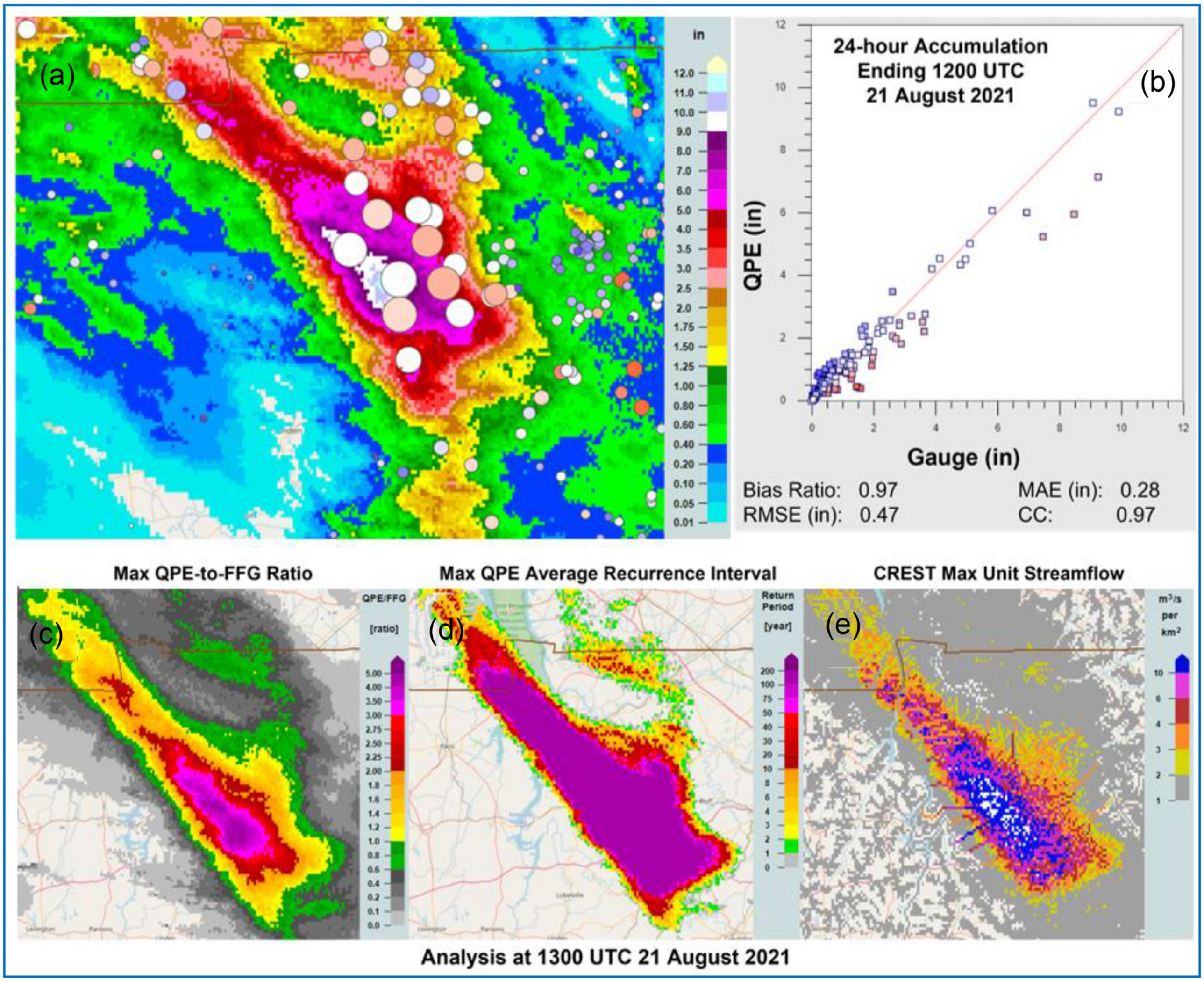


Fig. 2. (a) MRMS analysis of rainfall from an extreme rainfall event in Tennessee in August 2021 with bubble plots showing difference from gauge reports, (b) scatter plot showing MRMS and gauge differences, and (c–e) FLASH products derived from the MRMS rainfall estimates including the ratio of Quantitative Precipitation (QPE) Estimate to flash flood guidance, the maximum average recurrence interval of the rainfall, and maximum unit stream flow from a distributed hydrologic model.

attenuation distance. The simulations demonstrated that the model is adept at capturing the main climate characteristics of TC precipitation and the probability distribution of extreme TC precipitation in China, which is simple to run several hundred thousand times, with bright application prospects in catastrophe risk assessment.

4.2. Numerical weather model predictions of TC rainfall

Numerical weather model predictions were widely cited by all RSMCs and nations surveyed as a critical source of guidance for TC rainfall prediction. Global models and their ensembles, in particular, are used heavily as they provide coverage of entire TC basins, are easily accessible by most countries, and can be correlated to other forecast parameters such as the TC forecast track, intensity, and size. Global model forecasts are also more heavily used with longer lead times, particularly beyond 24 h, when observational data is less relevant and the TC is at a greater distance from the area of interest.

Several RSMCs, including La Reunion and Australia, noted concerns with global model performance for rainfall prediction in specific situations, particularly with small islands that have significant topography. The broad horizontal resolution does not allow them to adequately represent the orographic effects and associated enhanced rainfall. Other concerns with global models include inconsistent representation of deep convection occurring in the eyewall, as well as outer rain bands with smaller convective structures.

High-resolution models do offer improved rainfall predictability in some situations in which global models may be lacking, and do better anticipate localized, extreme rainfall events from TCs. It should be emphasized that high-resolution models often have a limited domain, and therefore are either not available, or are only available in a limited fashion, for some countries around the world.

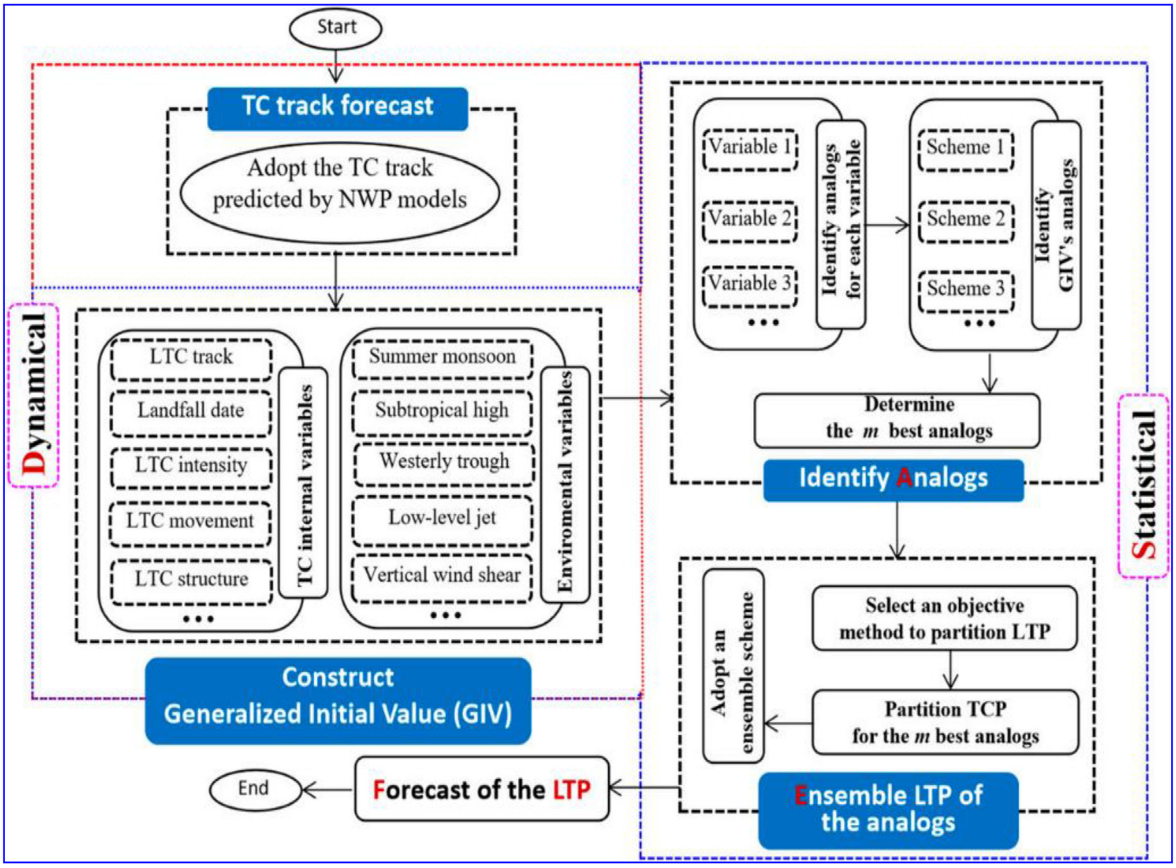


Fig. 3. Flowchart of the DSAEF model for predicting landfalling TC precipitation (LTP).

High-resolution models also tend to have a limited forecast time, and therefore gain increasing use and importance in rainfall forecasting within about 36–48 h of landfall. In particular, the high-resolution models seem to be most valuable when they can accurately account for storm structure, and for intense convective rain bands that develop along instability gradients or in the more unstable air around the periphery of a cyclone. This includes important insights well inland as a cyclone begins to decay and lose tropical characteristics, but still retains a tremendous amount of deep moisture. For example, the HRRR model accurately depicted extreme rain rates and potential for catastrophic rainfall with Hurricane Harvey in 2017 well to the east of the circulation center as the cyclone began to decay after landfall (Dowell et al. 2022). Additionally, hurricane models such as the Hurricane Weather Research and Forecasting (HWRF) model have made significant advancements in the past decade in model physics and data assimilation that have improved track and intensity forecast skill for tropical cyclones (Zawislak et al. 2022), but also provide increasingly realistic depictions of storm structure which can be valuable for determining the likely location of significant rain bands.

Besides the U.S.-based HRRR and HWRF models (in addition to multiple other hi-res models run by NOAA), another example is the AROME model developed by Météo-France (Fig. 6). Versions of the model have been implemented in the southwest Indian Ocean and in portions of the South Pacific. In fact, the horizontal resolution for the SWIO region was recently improved to 1.3 km over a vast area to better forecast TC rainfall (Faure et al., 2020). Australia has developed the Australian Community Climate and Earth-System Simulator-City model (ACCESS-C), providing higher resolution information over city domains. These are not the only examples, but are representative of the value that hi-res models can provide.

Ensemble techniques are particularly valued, to help quantify uncertainty. Multiple nations, including, but not limited to, India, Australia, and the U.S., reported using some version of a multi-model ensemble, incorporating ensemble data from a wide variety of modeling centers. India and RSMC New Delhi, for example, creates a Grand Global Ensemble, which is used extensively in forecasting rainfall. The guidance is generated on a GIS platform and used as an objective aid for forecasters.

In Australia, the Bureau of Meteorology uses the Operational Consensus Forecast (OCF) as the basis for any forecast rainfall. An intervention strategy has been created which allows meteorologists to make modifications to the gridded forecast rainfall based on local knowledge and experience (such as enhancements of rainfall due to topography). Likewise, the National Weather Service in the United States uses the National Blend of Models (NBM) as the starting point for all rainfall forecasts. Similarly, IMD utilizes multi model forecast duly modulated by operational forecasters through consensus.

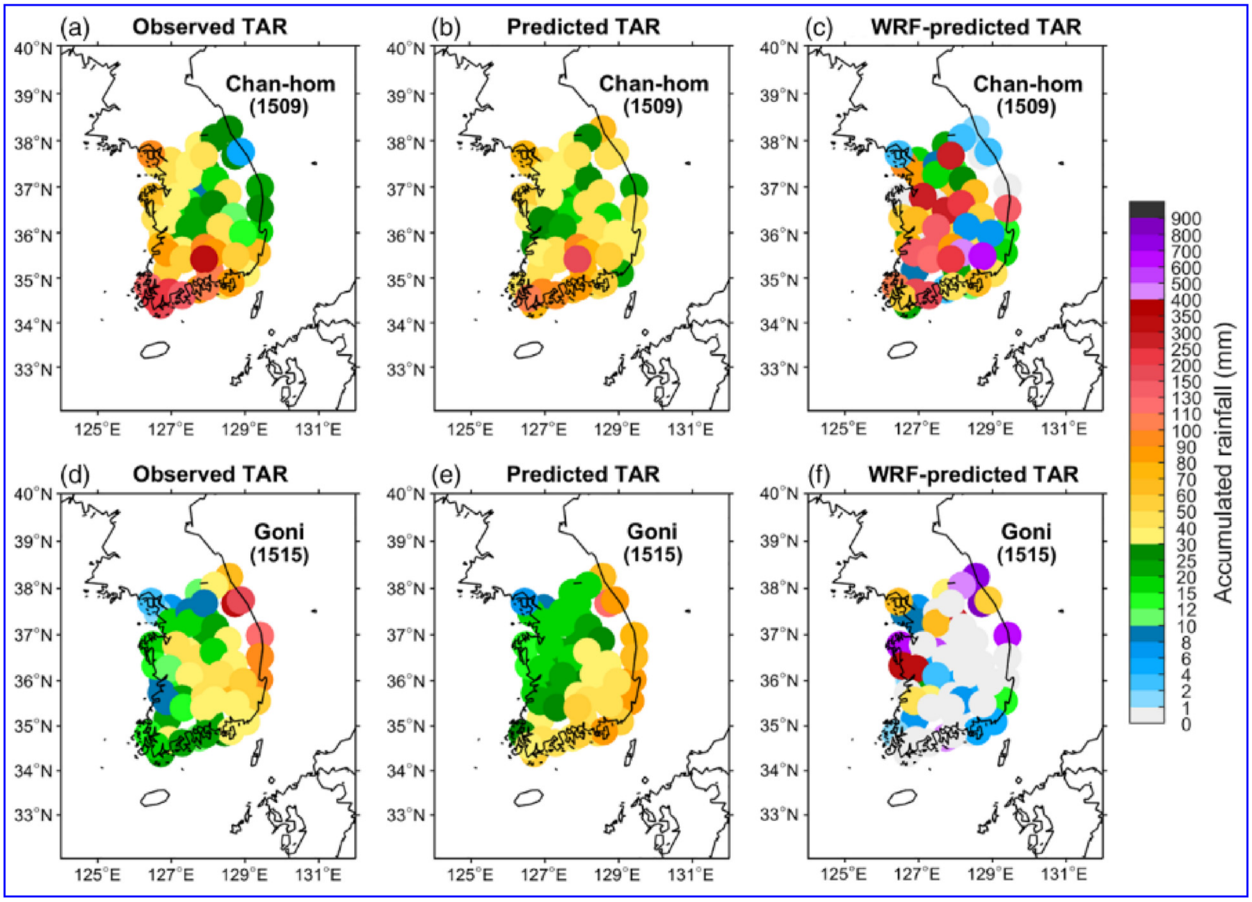


Fig. 4. Comparison of rainfall between observations (a, d) and simulations from statistical model (b, e) and WRF model (c, f) from 56 stations for typhoons Chan-hom (a–c) and Goni (c–f).

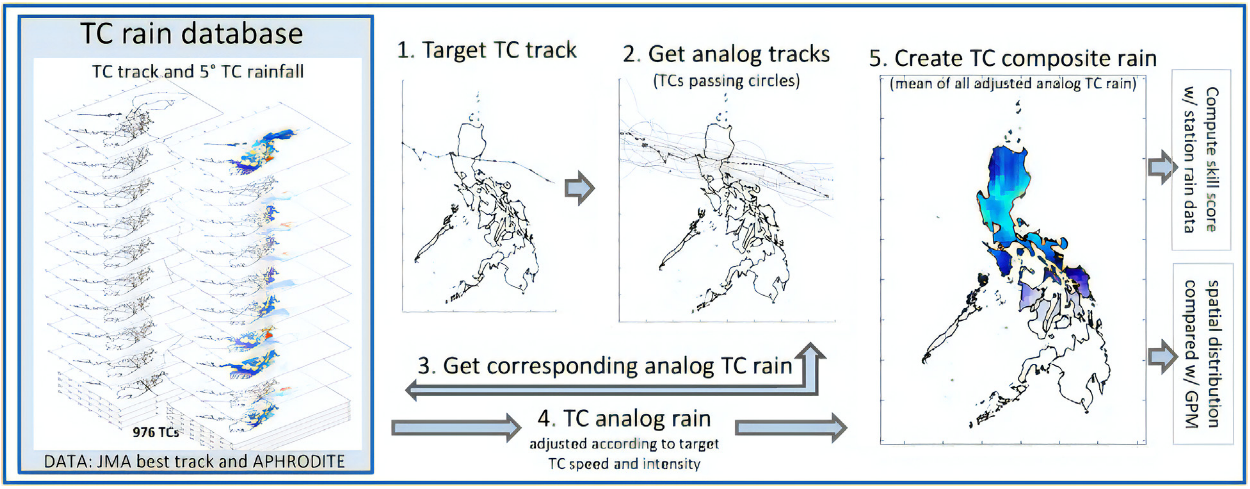


Fig. 5. Analog TC forecasting methodological framework from Bagtasa established in (2021).

Post-processing of ensemble data can also provide useful information for operational rainfall forecasts. In addition to probabilities of certain rainfall amounts, products like the Extreme Forecast Index, developed by ECMWF, can provide context on the relative rarity of projected rainfall, and the likelihood of significant rainfall extremes.

Finally, ensembles of high-resolution models can provide extremely valuable information. High-resolution models are able to more accurately depict fine-scale detail, but there can still be significant uncertainty in the placement or magnitude of a particular rainfall feature. For instance, high-resolution models may all correctly identify the potential for extreme

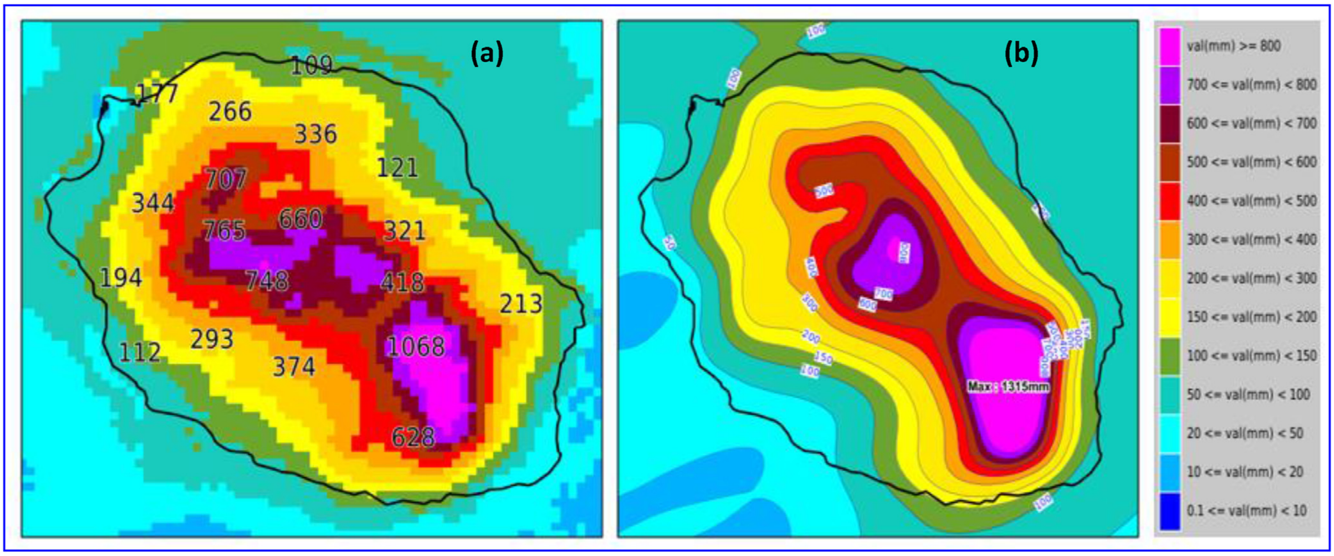


Fig. 6. Comparison of 24hr rainfall (mm) during Cyclone Batsirai in La Reunion in February 2022 with (a) observed rainfall and (b) AROME forecast.

rainfall in a particular outer rain band, but vary by 100 km on the placement. In these cases, high-resolution ensembles can provide probabilistic information and help identify most likely scenarios, and other plausible scenarios. RSMC La Reunion indicated an Applications of Research to Operations at Mesoscale (AROME) ensemble (2.5 km resolution) is currently being developed and expected to become operational in 2023 (Fig. 7). NOAA, in the United States, runs the High-Resolution Ensemble Forecast (HREF), which has a diversity of model cores, physics, and initial and boundary conditions that can be expected to capture a broader range of outcomes (Roberts et al., 2020). And development is occurring on the Warn-on-Forecast System (WoFS), another rapidly cycled high-resolution ensemble that would support a modernized probabilistic warning system. More information on WoFS is available in Yussouf et al. (2020).

5. Operational predictions and warnings

The status of forecasts and warnings by various RSMCs, flash flood guidance system and impact of riverine flow on flooding are discussed in this section.

5.1. Forecasts and warnings by various RSMCs

In general, all RSMCs are providing rainfall guidance in their official bulletins when land areas in their basins of responsibility are threatened. However, the issuance of official rainfall forecasts, warnings, and press releases occurs on a country-by-country basis, and therefore the formats and procedures vary by meteorological service. For instance, some countries provide forecasts and warnings specific to flooding and river flows, but others provide the overall rainfall and flooding risk with heavy rain warnings. Many countries use the same rainfall and/or flood related warnings for tropical cyclones as they do for non-tropical cases. Very often there is coordination with their national emergency and risk management agencies. Mohapatra and Sharma (2019) have described the procedure followed by IMD in India for forecasting the rainfall associated with TCs which includes (i) time of commencement, (ii) duration, (iii) area of occurrence and (iv) intensity of heavy rainfall.

In the U.S., the Weather Prediction Center (WPC) serves as a source of rainfall expertise in close collaboration with RSMC Miami (National Hurricane Center, NHC). As an example of rainfall guidance provided to other nations, WPC has an International Desk that began producing graphical quantitative precipitation forecast (QPF) guidance for TCs in 2016 for Central America, Mexico, and the Caribbean, and the guidance is closely coordinated with other forecasters at NHC and WPC. Although these products are not considered official, they are highly valued by national weather services as guidance tools when preparing the official forecasts for their nations.

Given the significant contribution of heavy rainfall and flooding to tropical cyclone fatalities, the U.S. NHC now prominently places rainfall- and flooding-related information in traditional forecast products, web pages, and in external communication including media interviews, social media, and briefings to public officials. Graphics depicting storm-scale zooms of rainfall hazard information for the United States are also located in a specific section for each storm directly on the main NHC web page.

For a TC affecting the U.S., the official forecast from NHC serves as the foundation for all rainfall and flooding forecasts. The WPC also serves as a specialized center of precipitation forecast. WPC develops an initial QPF- twice per day, which is then internally transmitted for collaborative editing from forecasters at local and regional offices through a collaborative forecast process (CFP), before final rainfall and flooding forecast products are issued. The CFP is important, as the River Forecast Centers (RFC) also use the QPF operationally to forecast river levels at key points along rivers across the U.S.

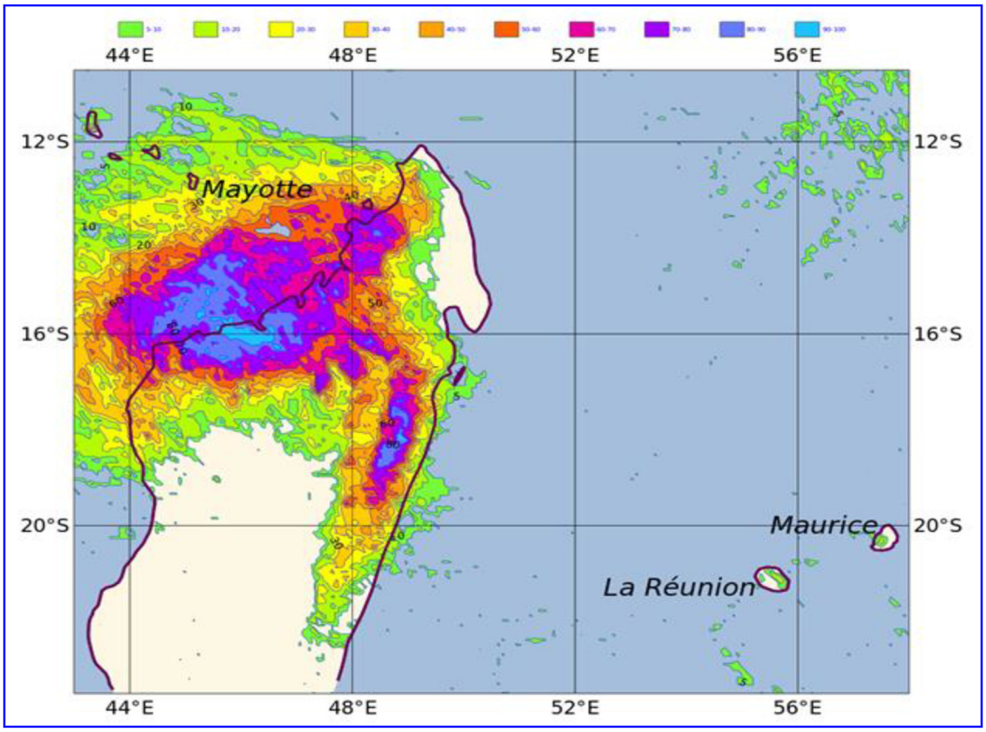


Fig. 7. Probability of exceeding 50 mm rainfall in 24 h via the AROME ensemble during Eloise in January 2021.

(Adams 2016). Therefore, numerous forecast products are adjusted in a consistent way with each update, and they all reflect an internally consistent scenario, which is valuable for public communication and briefings to key officials. WPC's prioritization of the official track forecast takes advantage of NHC's low track error when compared to individual model forecasts. This has led to similarly low displacement errors of WPC heavy rainfall forecasts, commonly improving on skillful multi-model blends by at least 10 percent (Table 1).

The verification of the directionality of displacement errors of the 2 inch forecast rainfall areas from WPC shows a clear tendency for heavy rainfall to be centered east and northeast of the forecast location (Fig. 8). This is due to prevailing westerly winds aloft and continental dry air wrapping into the western semi-circle of TCs favoring intense rain bands in the east of the center.

Yu et al. (2020) presented object-based verification results for rainfall forecasts of 25 TCs, encompassing 133 operational numerical forecasts, over China from 2012 to 2015. Forecast skill was highest for shorter lead times (24hr as compared to 48hr and 72hr), and for lower rainfall amounts. Results suggest that rainfall prediction will continue to improve with improved track prediction, but more work is needed on model initialization and the prediction of TC structure.

Table 1
Comparison of NHC track forecast errors, and the displacement errors of the centroid of WPC's 2 inch rainfall areas.

Forecast Projection	Lead Time	5-Year NHC Track Error (All Atlantic Cyclones)	Average WPC 2″ Rainfall Object Error (23 Landfalling Cyclones since 2016)
Day 1	24 h	58 km	90 km
Day 2	48 h	98 km	114 km
Day 3	72 h	146 km	158 km
Day 4	96 h	203 km	220 km
Day 5	120 h	277 km	445 km

Rainfall for TCs has traditionally been communicated in potential storm total amounts, which can occasionally lack some important context such as embedded rain rates and potential impacts. Burke et al. (2022) have found that WPC has been increasingly emphasizing the Excessive Rainfall Outlook (ERO), which basically conveys the probability of flash flooding (due to intense rain rates) within 25 miles of a point, in four tiers of risk, out to five days of lead time. The ERO has been found to be reliable as affirmed by Erickson et al. (2021), meaning that the forecast probability corresponds well with the rate of observed impacts. Therefore, it has become a powerful decision-making aid and is now being utilized in standard operating procedures that dictate disaster response for some jurisdictions in the U.S.

In the U.S., the primary rainfall-related warning is called a Flash Flood Warning due to the rapid hydrologic response to intense rain rates. Flash Flood Warnings are issued as polygons that contain the expected threat area. The polygons can cross geopolitical boundaries, such as state and county boundaries, to more precisely highlight the threat, and are separated into three potential impact tiers. The two most severe (considerable or catastrophic impacts) tiers of warnings are delivered to mobile phones within the polygon via the Wireless Emergency Alert (WEA) system. WEA alerts are intended to convey the most urgent, life-threatening weather information that necessitates a quick response.

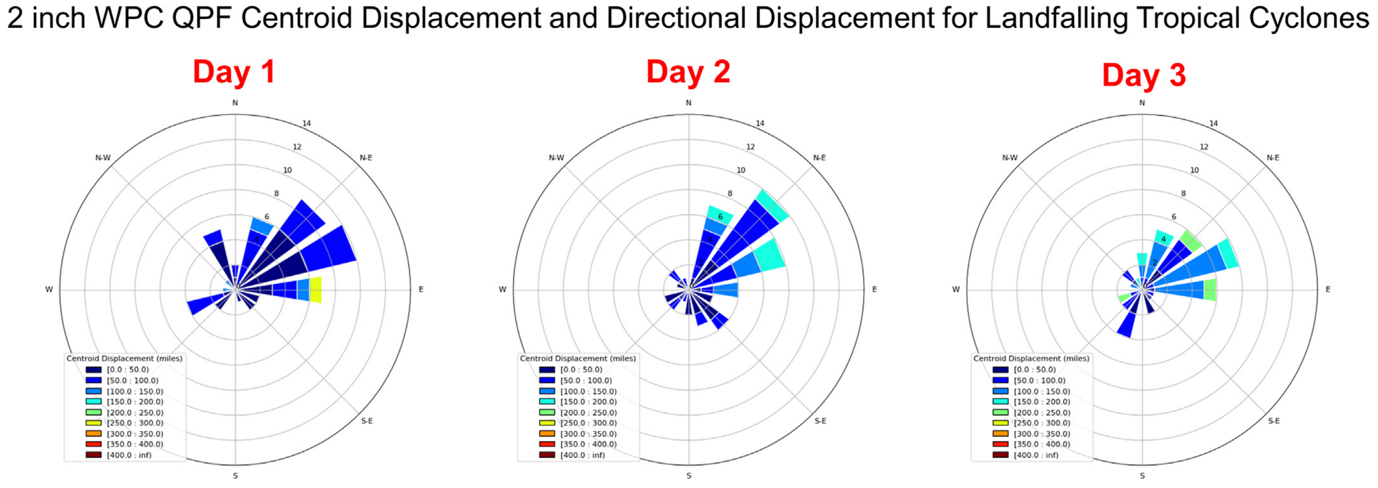


Fig. 8. Displacement errors of the forecast 2 inch rainfall areas for tropical cyclones from NOAA's WPC grouped by forecast lead time, and colored by the magnitude of the displacement.

In Japan, mobile device alerting has also been developed via a 1 km mesh "real-time risk map" (Fig. 9) with 5 levels of colors to indicate the current and predicted risk level at each location, depending on how close it is to the predetermined warning threshold in which past disasters occurred, and taking the vulnerability of the area into account. The risk distribution is used to supplement official weather warnings, and is automatically created, announced, and updated every 10 min. JMA has collaborated with private companies to launch a service in 2019 that notifies users on their smart phones and other devices when the risk increases at their location.

Many countries have adopted a tiered warning strategy for rainfall, represented by different colors or some other method. For example, IMD provides impact-based heavy rainfall warnings along with designated color code based actionable warnings for all major cities covering all major state capitals. It is a three stage, impact-based heavy rainfall warning system which includes advisories, alert and warnings. IMD is also implementing an integrated flood warning system for urban areas countrywide. It has already established this system at Chennai and Mumbai cities which are highly vulnerable to floods. This system has a disaster preparedness decision support system that also incorporates coastal flooding.

BMKG (Meteorology Climatology and Geophysics Council), Indonesia uses a tiered warning service for heavy rain with 4 tiers that include No Alert, Advisory, Watch and Warning.

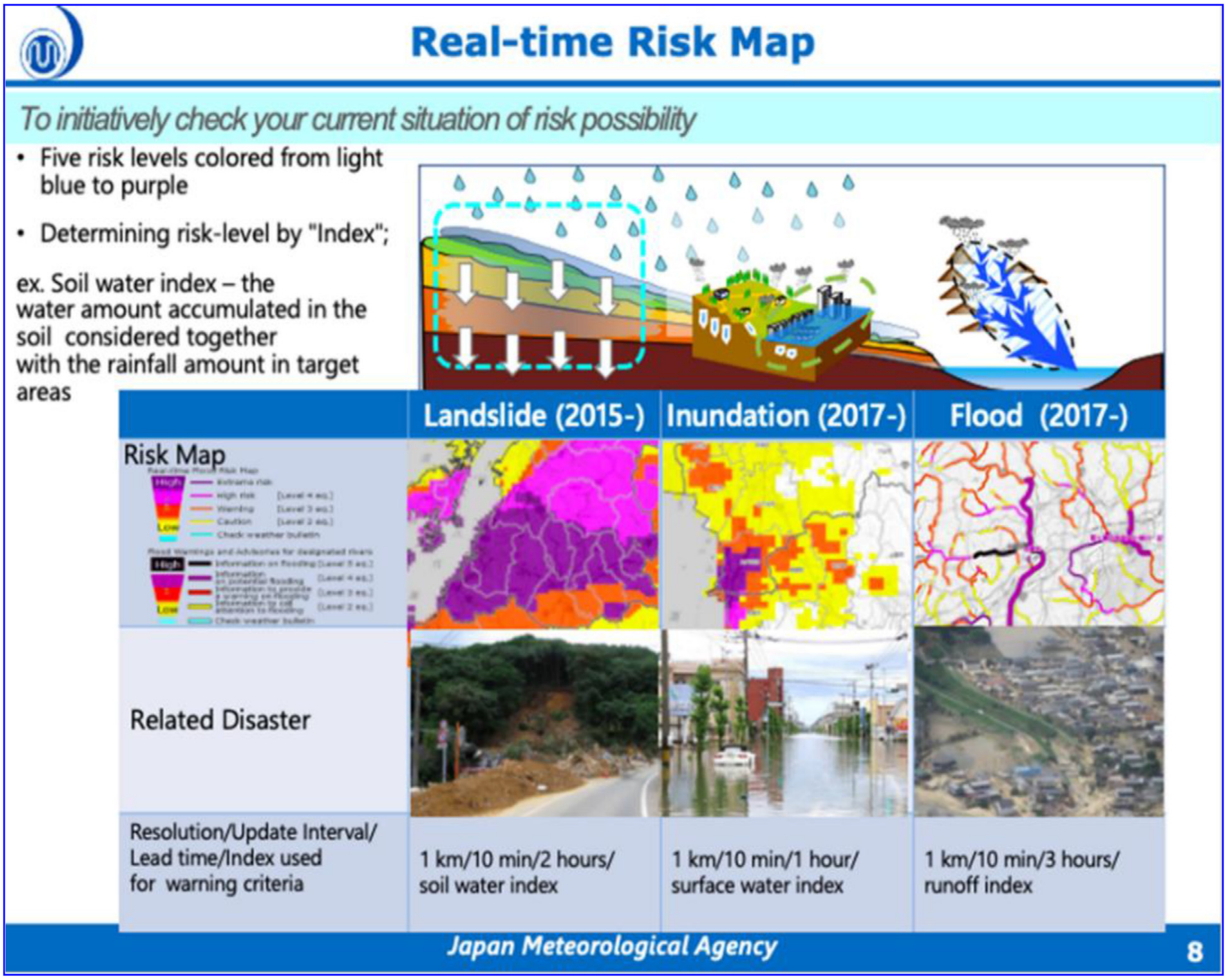
Common challenges for forecasting and warning for TC heavy rainfall were outlined by the Bureau of Meteorology in Australia, but are applicable to all other TC basins to some degree:

- Global numerical weather prediction models can provide poor forecast rainfall guidance around small island countries, especially those with significant topography, or small-scale topographic features in continental areas.
- High-resolution model guidance is not reliably available in all areas of the world
- Some areas have limited or no radar coverage
- Varied coverage of automated weather stations and rain gauge networks
- Displacement of heaviest rainfall far from a tropical cyclone center in peripheral rain bands. This is a common issue with the Central American Gyre (Papin et al., 2017) and other broad monsoonal low pressure systems around the world, and the role they play in the genesis and evolution of TCs. A classic example is with Tropical Storms Amanda and Cristobal in 2020, which developed in association with the Central American Gyre.

5.2. Other warning guidance and thresholds

The World Meteorological Organization (WMO), in partnership with multiple U.S. government agencies started a Global Flash Flood Guidance System project to support additional guidance for hydro-meteorological events developing rapidly after the initiating rainfall. The U.S. has previously been operating with flash flood guidance, which is integrated into U.S. warning processes and products such as the Excessive Rainfall Outlook (ERO) mentioned above in section 5.1. Key objectives of the Global Flash Flood Guidance System (FFGS) are to enhance the capacity of national meteorological and hydrological services to issue effective warnings and alerts, enhance collaboration and development, support flash flood early warning products, provide training to forecasters, and support the WMO Flood Forecasting Initiative.

The use of this tool can bridge the gaps between the four components for effective early warning systems: risk knowledge, monitoring and warning service, dissemination and communication, and response capability. The aim of the FFGS is to provide a diagnostic value (known as flash flood guidance) that estimates the amount of rainfall of a given duration within a watershed that is required to produce flooding at the outlet of the catchment. The FFGS is designed to update its values in time and space and to "remember" rainfall that has already occurred in the catchment. In this way, the FFGS takes account



Real-time Risk Map

To initiatively check your current situation of risk possibility

- Five risk levels colored from light blue to purple
- Determining risk-level by "Index";

ex. Soil water index – the water amount accumulated in the soil considered together with the rainfall amount in target areas

	Landslide (2015-)	Inundation (2017-)	Flood (2017-)
Risk Map			
Related Disaster			
Resolution/Update Interval/ Lead time/Index used for warning criteria	1 km/10 min/2 hours/ soil water index	1 km/10 min/1 hour/ surface water index	1 km/10 min/3 hours/ runoff index

Japan Meteorological Agency

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Fig. 9. Design of the real-time risk map for flooding from JMA.

of antecedent catchment conditions and can calculate the amount of additional rainfall that is needed in order to produce flooding. When these values are used in real time, they provide an objective basis to generate flash flood warnings.

As of this report, there were 4 operational regional FFG projects listed by the WMO: Central America (CAFFG), southern Africa (SARFFG), Mekong River region (MRCFFG), and the Black Sea and Middle East (BSMEFFG). At least 9 other regional projects were under development.

Other thresholds are used to inform rainfall- and flood-related warnings. The Bureau of Meteorology in Australia issues Severe Weather Warnings for heavy or intense rainfall when the rainfall over a period between 30 min and 6 h is expected to exceed the 10% or 2% Annual Exceedance Probability (AEP), respectively. The AEP is the probability that a rainfall amount over a given period will be exceeded in any one year.

Rainfall exceedance of FFGs and AEPs can also be built into modeling systems and observational platforms. For instance, in the U.S., the High Resolution Ensemble Forecast (HREF) provides probabilities of exceedance of both, and, as detailed in section 5.1, the MRMS system compares real-time rainfall estimates with such thresholds as well. These tools are used by forecasters to inform a wide variety of outlooks and warning products.

5.3. Flooding and river impacts

All regions reported that flooding from rainfall was among the most destructive, costly, and deadly impacts from tropical cyclones. Many of the impacts come from inundation resulting from excessive runoff, particularly along streams and rivers, in urban areas, and in areas of steeper terrain. Yang et al. (2020) showed that the established links between TC flooding and climate controls present a potentially predictive tool of TC flood risk over China and other East Asian countries under future climate conditions.

IMD in India also noted additional impacts that commonly occur from the combination of rainfall and storm surge in coastal areas, landslides (including in areas very far inland), large scale soil erosion and weakening of embankments, and to people whose normal sheltering location is severely damaged or destroyed by severe winds.

Approaches for hydrologic modeling vary from country to country, and are mostly dependent on individual national meteorological and hydrological services. In general, uncertainty related to rainfall magnitude and placement is the dominant factor for determining flooding impacts from TC rainfall, including future river flows. However, other uncertainties are still important, including antecedent wetness of the soils, land use type, drainage basin characteristics, among many others. This introduces considerable complexity to the challenge of forecasting how rivers and streams will respond to an approaching TC, and the resulting inundation.

For instance, India uses two approaches simultaneously including (a) historical database with damages and (b) an impact model using vulnerability and exposure datasets with relevant meteorological and hydrological information. Other forecast centers use multiple approaches as well. La Reunion uses some physical models that try to reproduce rather faithfully the processes leading from the rainfall to increasing river levels, and some statistical models that try to link given rainfalls with river flows based on past events.

In the United States, the National Water Center (NWC), is currently building operational capacity and will be the center of expertise for hydrology, as WPC is a center of expertise for rainfall forecasting. WPC and NWC are developing a close working relationship with regular collaboration between meteorologists and hydrologists to try to improve prediction of flooding with regular discussions between experts from different, but related, disciplines. This collaboration includes input to the official statements in NHC forecast products for the U.S. Two other important items in development at NWC include the National Water Model (NWM), a hydrologic modeling framework that simulates observed and forecast streamflow at millions of stream locations, and flood inundation mapping (FIM), that graphically depicts the potential spatial extent of flood waters and, in some cases, the expected depth. Future versions of the NWM may more fully couple multiple processes. These tools are expected to complement traditional river forecasts and warnings that are based on the official, collaborated rainfall forecast (QPF), and are produced for approximately 3600 key locations such as larger cities. A goal of NWM and FIM is to provide a complete and detailed picture that can be used for critical decisions such as deployment of search and rescue resources.

The Global Flood Awareness System, part of the Copernicus program in the European Union, provides some forecast guidance for certain rivers across the globe based on rainfall inputs from the ECMWF ensemble, and thus may be a resource for a variety of countries.

6. Summary and conclusions

Flooding from heavy rainfall leads to fatalities more often in TCs than any other hazard. Some of the costliest and deadliest TCs in recent years have delivered massive tolls largely because of rainfall induced flooding. Therefore, improvements in understanding of the science of TC rainfall, forecast accuracy of heavy rainfall, generation of impact based forecast & risk based warnings and improvements in communication of rainfall & flooding forecasts is of critical importance. There are still constraints wrt. the observational network in terms of below optimum rain gauge network and limited radar coverage globally. The global numerical weather prediction models generally provide poor rainfall forecast wrt heavy rainfall events, topographically sensitive regions and normally have large scale spatial & temporal errors. Also, the high-resolution model guidance is not reliably available in all areas of the world. To address these issues there is need to augment observational network optimally, improve modeling & research studies, attempt effective utilisation of artificial intelligence & machine learning techniques in conjunction with numerical model guidance, improve availability of high resolution models and ensembles for more regions via enhancement of collaboration between researchers, operational scientists including meteorologists & hydrologists, social scientists and disaster management agencies for better predicting TC associated rainfall and mitigate associated impact.

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